VOLCANIC DIFFERENTIATION OF IO

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The intense volcanic activity on Io, if sustained over geologic time, should have strongly differentiated the silicate portion of this Jovian moon. We will show that this differentiation is likely to have produced a low density, silica- and alkali-rich crust about 50 km thick. This is similar to suggestions made previously by Crumpler [1].

Io is the most volcanically active body in our solar system. Ground-based measurements show that Io currently radiates ~10^{14} W above the conductive heat flow [2]. This heat is dominantly supplied by tidal heating and is largely transported to the surface via volcanism [3]. 10^{14} W can generate roughly 2500 km^3/yr of silicate melts. We reduce this number by an order of magnitude to conservatively account for the possibility that in recent decades Io has experienced an unusual level of tidal heating and/or volcanic activity, which seems likely considering that Io's current heat flow probably exceeds the theoretical upper limit to steady-state tidal heating [2].

Thus, over 4 billion years, we conservatively estimate that Io should have produced 10^{12} km^3 of silicate magma. However, the total volume of Io is $2.5x10^{10}$ km^3. Since the production of magmas involves partial melting, this suggests that the silicate portion of Io should have undergone, on average, well over 100 episodes of partial melting. This surely has resulted in extensive differentiation.

We have attempted to place some quantitative constraints on this differentiation. Our conceptual model has the partial melting concentrated at a single depth. The idea that tidal heating is deposited in a relatively narrow depth region (i.e., a 50-100 km thick asthenosphere) is supported by some theoretical models [4]. In our conceptual model, the buoyant liquids generated at this depth are transported toward the surface and the dense residue sinks away. The solidified melts would be carried back down to the zone of melting by burial and subsidence. The depleted mantle would also eventually be brought back to the melting zone by convection, especially if deep mantle dissipation of tides is important. Io's large-scale topography can be partially explained by the addition of ~1/3 to 1/2 heating from deep mantle dissipation to the heating from asthenospheric disssipation [5].

We use the MELTS program [6] to examine the differentiation taking place within this melting zone. The MELTS program uses mathematical expressions for the various thermodynamic parameters to calculate the equilibrium mineral assemblage and melt composition given the temperature, pressure, oxygen fugacity, and bulk composition of the system.

Our first step before using the MELTS program was to estimate a reasonable starting composition for Io's mantle (Table 1). CM chondrites have been suggested to be a plausible bulk composition of Io [7]. From this bulk composition we extracted an Fe, Ni, S core comprising 20% of the mass of Io [8]. All the sulfur (~5 wt.% of CM chondrites) is placed in the core. While there is sulfur at the surface of Io, it appears to be volumetrically minor. (If all of the sulfur evolved to the surface it would form a layer ~50 km thick, which is not consistent with topographic observations [9]). However, the presence of elemental sulfur on Io would indicate that Io is highly reduced, hence we have used the Fe-FeO buffer for oxygen fugacity. Other choices of oxygen fugacity should have little effect on the following discussions.

For our baseline model, we have placed the zone of melting at 10 kbars (~200 km depth). We further assume that the melt would escape the zone of melting at 10% partial melting. Both the resulting melt and residue were again subjected to 10% partial melting. These products were then partially melted again and again, for a total of 4 episodes of differentiation. More episodes were not calculated because (1) there is a geometric increase in the number of compositions to deal with, (2) the volume of most of these products is miniscule, and (3) further runs produce compositions that are outside the range where MELTS is calibrated (e.g., alkali contents >30% or melt temperature <1000 K).

Our baseline run differentiated Io's mantle into 1.9% andesite, 0.8% basaltic andesite, 7.3% gabbro, 9% ultramafic magma, and 81% depleted peridotites and dunite. It is difficult for the ultramafic melts (average density 3.11) to rise through the 50 km thick andesite-gabbro crust (average density 2.87). It should also be noted that the calculated crustal compositions are very alkali-rich, ranging from 19-8 wt% Na_2O+K_2O. The alkali silicates should react with S to form alkali sulfides [10] and/or with SO_2 to form alkali sulfates [11]; either the sulfides or sulfates could be sputtered to supply the Na and K observed in the atomic Io clouds.

The general result that Io should form an approximately 50 km thick, silica and alkali-rich, low density crust seems robust to changes in the depth of the melting zone, increasing the fraction of melt before escape, or the addition of substantial initial water [Table 2]. The water is lost extremely efficiently in 2 episodes of partial melting.

While the general conclusion about Io's crust appears robust, we caution the reader that our modeling is extremely simplistic. For example, (1) Io's initial composition is uncertain, (2) fractional crystallization and assimilation are ignored, (3) melting probably takes place over some range of pressures, (4) we completed only 4 episodes of partial melting, not >100.

We end by noting that the extremely hot lavas (>1500K) observed from the ground [2,12] require an explanation. Given the speed of radiative cooling, even in airborne fire fountains, a brightness temperature of 1500K requires a magmatic temperature of at least 1700 K, typical of ultramafic melts. This suggests to us three possibilities. First, the tidal heating and volcanism on Io might be geologically recent and Io might not be extensively differentiated. Second, we may be seeing lava compositions unheard of on Earth, resulting from extreme differentiation. For example, pure sodic nepheline ($NaAlSiO_4$) has a melting point of 1800 K while its potassic version ($KAlSiO_4$) melts at 2020 K. Or, thirdly, the very dense, ultra-mafic melts may be able to penetrate the low density crust. This is plausible if the lowest-density materials are patchy, allowing the dense liquids to erupt through the intervening areas. These patches of low density crust might be manifested as the isolated 2-10 km tall mountains and plateaus on Io. The lowest density magmas could be rather viscous, forming large plutons (perhaps 10s of in kilometer scale) that freeze before they reach the surface but provide the buoyancy to isostatically maintain/raise the mountains. This hypothesis might help explain why there is no correlation between mountains and elevated surface temperatures.

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Table 1. Estimated Initial Composition for Io's Silicate Mantle (wt.%)

SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
44.26	0.16	3.53	0.68	16.05	0.33	31.03	2.95	0.90	0.11

Table 2. Model Crustal Properties for Io.

	BASELINE	P = 1kbar	1 wt.% H2O	F = 25%
Crust thickness	54 km	63 km	54 km	40 km
Crust density (g/cc)	2.87	2.69	2.65	2.78
Lava types	Andesite-Bas. And.	Rhyolite-Dacite	Andesite-Bas. And.	Bas. And.-Basalt
Eruption temps (°C)	1010-1067	1000-1117	625-1064	1020-1091